Design framework of a Configurable Electrical Power System for Lunar Rover

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***Abstract*—**The temperature swing over lunar terrain is harsh and it can fall to as low as 70K during lunar nights in the polar region[1], which has significant interest as a preferred landing site. Most of the lunar rover designs incorporate, radioisotope heater units (RHU) to maintain the temperature during the nights. A 50W electrical power system (EPS) design for a Lunar rover, which does not contain a radioisotope heater units, is presented. The design approach adopted, provides wide operational flexibility and enhances the survivability of the Rover, in the extreme environmental conditions and unpredictable terrains present over the moon. The design conserves the battery capacity for recovery from unfriendly terrains or for an extended power requirement by a scientific experimental payload. The design concept is verified in lab conditions, by making a functional verification model.

***Keywords*—**Electrical Power System; Battery Powered Vehicles; Planetary Rovers; Solar cell arrays

I. Introduction

Many agencies globally are involved in the development of lunar rover, for conducting various scientific experiments on the lunar terrain[3][7]. The temperature swing over lunar terrain is harsh, as it varies from around 70K during night at the polar region[1] to 384K at the equator during the day time[2]. The data from Clementine Long-Wave Infrared (LWIR)[2] for the lunar surface temperature with Sun at noon conditions and at zero latitude is shown in Fig. 2(a)[2]. The estimated lunar surface temperature at 90°S latitude, with zero inclination is shown in Fig. 2(b)[1].The harsh lunar environment, in terms of extreme temperature variations are considered to be a challenge in the survivability of the rover. A number of lunar missions to land a rover, have ended up prematurely, due to failures induced by the severe low temperature during the lunar nights[7]. Most of the lunar rover designs incorporate, radioisotope passive heating units (RHU) to maintain the temperature during the nights. In a rover design, that does not have the RHU, the extreme cold swing of the temperature is particularly damaging to the batteries of the Rover, as the freezing of electrolytes can cause permanent failure[16].

It is important for the overall survivability of the lunar mission, which does not contain any RHU, that the design of power system is more accommodative to the possible failure scenarios of batteries, due to the lunar operating conditions[8].

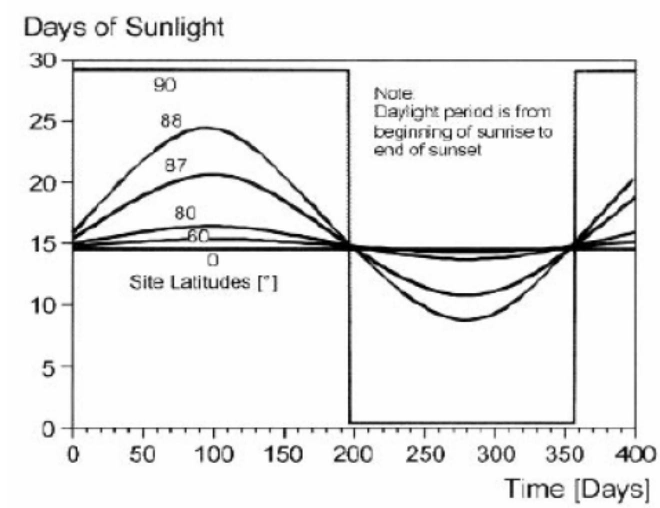


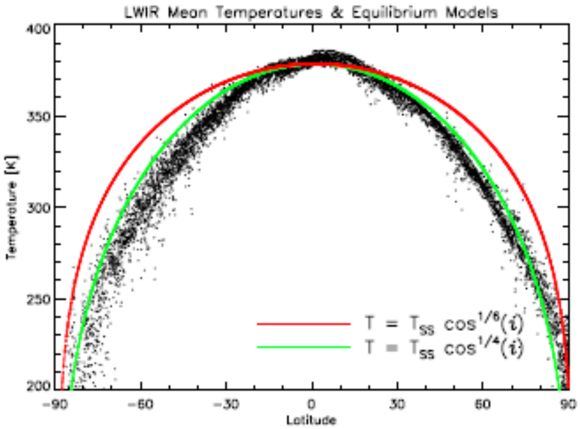
Fig. 1. Number of days of sunlight per month during the year for different lunar latitudes[6]

Power system design approach for the AMALIA Moon rover has been reported in [4]. Also, energy management strategy for a lunar rover is discussed in [5].

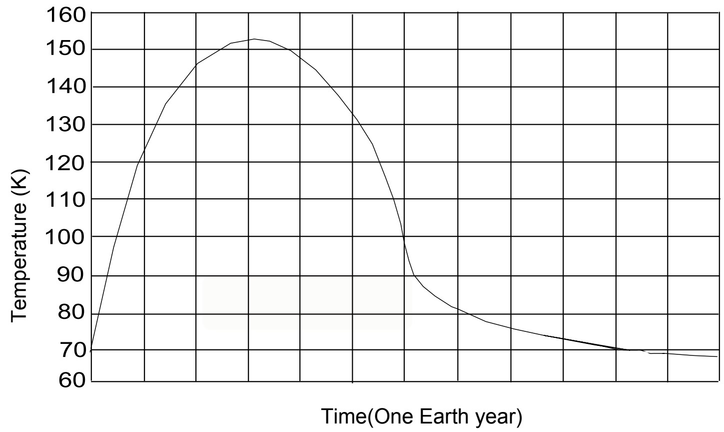
Reconfigurable systems can attain states with new capabilities. This can enhance the survivability, by maintaining some level of overall functionality by the way of reconfiguring. The design should address majority of possible scenarios, which can lead to a gradual or sudden power failure[9].

The scope of lunar rover's power requirement differers widely from the perspective of the overall mission objectives. This paper presents an electrical power system design for a small lunar rover of 25Kg class, and having a power budget of 50Watts. The design utilizes well proven analog space grade active and passive devices, while keeping the complexity and weight to a minimum level.

The landing site preferred by many of the missions are in the southern lunar hemisphere, a zone around 70° to 90° south latitude, which receives a good solar illumination[2]. This zone has many planes those are suitable for conducting a landing experiment. This lunar day profile for the possible landing location for different latitudes for an year long period is shown in Fig. 1[6].



(a)



(b)

Fig. 2. Lunar surface temperature (a) Clementine data for Sun at noon and at zero latitude[2] (b) Estimated surface temperature at 90°S latitude, with zero inclination[1]

II. Operational features of Power System

The power bus design caters to the following operational features, which are important for improving the survivability of the rover.

- Minimal drain on the battery during the launch and transit phase of the mission. During this time rover is kept in power off condition and assembled to the drop-down platform of the lander. This is to ensure that, the battery is holding sufficient state of charge (SoC), during the initial phase to support the solar panel deployment and roll down from the lander drop down platform.
- Sleep and wake-up logics to address the initiation of automatic power shut-down, at the on set of lunar night and automatic power ON, whenever lunar day begins. This makes sure that the entire lunar rover hardware gets switched off at the onset of lunar night. This improves the survivability of all the electronic systems, as they are not qualified for an active state during the extreme cold weather. Making them to pass through the lunar night in a passive state, improves the probability of survival. The wake-up logic ensures that the activation of all rover circuitry happens only after the rover temperature builds up to a conjunctive level of $0°C$ or more.
- A feature to preserve the battery capacity before night falls, as the extreme cold survivability of battery enhances with higher state of charge. This is achieved by adding a command-able battery isolation, that makes the power bus to be sourced only from the solar panels. This is a planned activity, after which no movement of the rover will be carried out till the wakeup on next lunar day. This allows for continuation of on-board experiments, till the rover falls to sleep after the temperature fall below -4$°C$ or after the sun set, whichever happens first.
- Automatic disable of battery charging whenever the temperature is $\leq 0°C$. This prevents possible damage to the Li-ion battery, as charging at very low temperature can lead to a short mode failure of the cell[16]. The entire solar generation during this time is used for heating the battery as well as other rover electronic systems.

III. Power Sources

There are many proposals of the power source options for the planetary surface vehicles[10][11]. The power sources on-board the proposed rover is fixed (deployable but not independently sun tracking) solar panel, made of space grade triple junction solar cells, and a 3Ah capacity battery made of [15] low temperature Li-ion rechargeable cells [15]. The generation capacity of the solar panel is around 50W, at normal incidence of solar radiation.

The battery is crucial during the post landing operation phase, where the rover rolls down from the lander craft after touch down. Also the operations to deploy the solar panels are done before the roll down. The batteries can be discharged till the casing temperature drops to -20$°C$, while charging is done only above $0°C$. This is as per the manufacturer's recommendations[15].

The solar panel is deployed by issuing commands from the ground control center, after the touch down of the lander craft, and after waiting for the settling of the lunar dust. The solar panel is oriented to receive maximum solar energy by orienting the rover accordingly, while moving or otherwise. Solar cells are placed on both sides of the panel, so that generation can happen from either side, depending on sun position.

IV. Power Bus Configuration

The power bus is planned to be of 16.5V to 21V range, as the maximum power conception is only around 40W. The power bus design allows reconfigurability of the bus. The simplified configuration is shown in Fig.3. The Bus isolation Logic (BIL) is designed to configure the power bus in following modes.

1) Battery tied bus (BIL selects path B): In this case, battery voltage decides the bus voltage. Battery

gets charged with a current, decided by the instantaneous generation($I_{generation}$) and the load requirement(I_{load}).
$I_{charge} = (I_{generation} - I_{load})$.

2) Sun-lit regulated bus with battery support (BIL selects path C) : Bus voltage is regulated to 21V during sun presence, while dipping to battery voltage when sun is absent. Note that the small size lunar rover can experience frequent sun absences due to local shadows. Also battery supports the peak current demand by the wheel drive motors for climbing up or for running over obstructions.
3) Sun-lit regulated bus with battery charging (BIL selects path D): This is similar to the previous mode, with the exception that, battery gets charged with the excess current ($I_{generation} - I_{load}$)).
4) Sun-lit regulated bus with disconnected battery (BIL selects path A): This is solar generation alone configuration, where battery is disconnected from the bus. Advantage of this mode is that, configuring to this state, just before the lunar night, can help in retaining the battery capacity, which will enhance the chance of survival of the battery during the lunar night. Also, in case the battery does not survive the lunar night, the mission can still be on track.

The overall power bus configuration is shown in the Fig.4, and the battery isolation logic is shown in Fig.5. This scheme provides the flexibility to configure the bus as in different modes as discussed above. The mode selection for the power bus can be done by ground command, and some initialization of the modes are done at turn ON and turn OFF of the rover automatically, as discussed in the following subsections. The switches (P-channel MOSFETS) are made ON or OFF and the four possible combinations results in selection of path A, B,C or D for the BIL as discussed above.

A. *Rover Power ON initialization*

Q_2 is made ON, and Q_1 kept OFF. Battery can only do a discharge of the demanded current. In effect, bus is configured as sun-lit regulated bus with battery support. The switches Q_1 and Q_2 are configured in this fashion, whenever the Rover is powered ON (S_1 is closed). This prevents charging current flow into the battery, immediately after the power ON of the rover, during that time, temperature may be in a near zero condition. At the same time battery provides the peak current support for the wheel drive motors, if necessary, as the switch Q_2 is in ON condition.

Initializing the bus to this mode, ensures that, the rover turns ON, even if the battery has underwent a short mode failure during the just ended lunar night. If the battery is in a good condition, no charging of battery takes place automatically, as the rover battery may be still not in a thermally comfortable zone to get charged. At the same time, battery discharge is possible, which allows the rover, to drive to a more comfortable location to get more sunlight or to do a payload operation.

B. *Rover Power OFF initialization*

The switches Q_1, and Q_2 are made OFF on power shut down. So that, the drain on the battery is minimal($\approx 50nA$), and ensures that the power-bus is not clamped down by a failed/ faulty battery, during the wake up. This is crucial as, batteries are prone to failures due to crystallization and seal leak break during storage in extreme cold conditions[16].

C. *Bus re-configuration*

There is a command provision to make the switches Q_1, and Q_2, ON or OFF separately from the ground, and this allows the reconfigurability of the power bus. This is shown in Table I.

TABLE I. DIFFERENT CONFIGURABLE STATES OF THE BUS CONFIGURATION

States	Q_1	Q_2	Functionality	Remark
1	ON	ON	Battery Can get charged & Discharged	Battery Tied Bus Configuration
2	OFF	ON	Battery can only Discharge	Sun-lit Regulated Bus configuration, This configuration is initialized after Rover is made ON
3	ON	OFF	Battery can only get charged from the excess generation available	LTP/UTP control prevents over charge
4	OFF	OFF	Battery is fully isolated from the Power Bus	Preserves the Battery Capacity, When rover goes OFF, this state is initiated

D. *LTP/UTP based Sunlit bus regulation*

The control of shunt switches for the bus regulation during sunlit time utilizes the differential comparator based LTP/UTP control[13]. The LTP/UTP control range for the bus voltage rgulation is set between 20.5V and 21V. The value of the bus-capacitor is chosen to limit the frequency of shunt switch operation to a value less than 2KHz[12].

E. *Pre-wake-up heating & Regulator*

The pre-regulator, which is active only when the rover temperature is less than $0°C$, is a shunt linear regulator, which regulates the bus to 10V. The dissipated heat is used for rising the rover temperature to a level above $0°C$ (average temperature inside the rover equipment bay). This also acts as an initial supply to all the circuitry that need to work before the wake-up function, like temperature logic. The control range of the pre-regulator is shifted to 22V, after the above 0°C condition is achieved. This voltage level is more than the LTP/UTP control range of 20.5V to 21V. Hence it acts like a redundant controller, which can regulate the bus in case of a failure of the LTP/UTP control or open mode failure of the shunt switches.

F. *Wake-up logic*

The block schematic of the proposed rover power system configuration is shown in Fig.3. The wake-up of the rover happens, with closure of the switch S_1. The activation of wake-up is based on satisfying the following conditions.

- Rover temperature $\geq 0°C$. All of the generated solar array output, before wake-up, is used for heating of the equipment bay of the Rover. This, together with direct

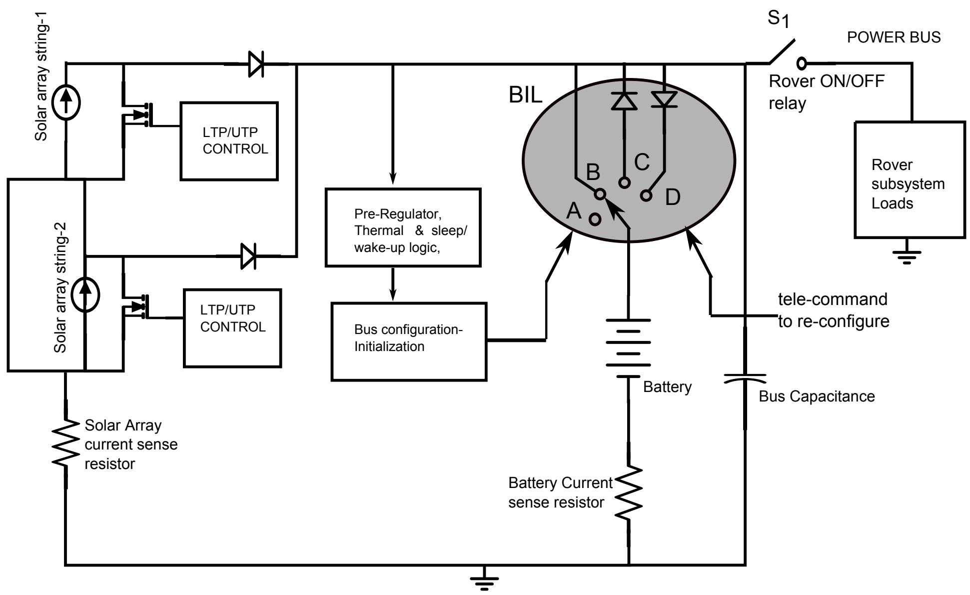


Fig. 3. Proposed Simplified Configuration diagram of the Power Bus formation for the Lunar Rover

sun load helps in building up the rover temperature after an extreme cold lunar night.

- The solar panel generation can support a load of 1A at 18V or the battery can provide a current of 1A at 18V. Before the wake-up, health of the battery(the battery is connected in discharge mode to the bus during this time) or the generation from solar panel is verified by connecting the bus to a heater load of $\approx$ 1A, for around 20ms. If bus voltage is maintained above 18V, with the 1A load, wake-up is carried out. This check ensures that, after the closure of S_1, bus can support the minimum bus load of 1A.

G. Wake-up Enable or Disable

During the launch/ transit phase, any accidental wake up of the rover can go unnoticed, and can result in draining of the entire battery capacity before the rover is on lunar surface. This can lead to a mission failure, as battery capacity in the initial phase of the rover landing is very important. To prevent this, a wake-up disable or enable feature is provided. This can be initiated only by a wired command, either from the ground test equipment or from the Lander craft. This is shown in Fig.4.

H. Sleep Logic

the sleep logic is an automatic initialization of a power shut-down by opening S_1 in Fig.4. The activation of this is based on the Bus voltage becoming lower than 16.5V. There is a provision to initiate the sleep function by tele-command (TC), provided the lunar night has set in. This command is labeled as Forced sleep command in Fig.4. This command remains non functional during the sunlight period. Fig.6 shows the flow diagram for the sleep and wake up logic operations of the rover.

V. Hardware Implementation

The functional verification model (FVM) of the rover is realized and tested. The realization utilized generic space grade components like LM111 comparator, OP07 operational amplifier etc. and other passive components. Also, instead of bipolar transistors, MOSFETs are used in all circuits because of their better low temperature behavior[14]. The circuit implementation of Battery isolation logic (BIL) is shown in Fig.5. The configuration of P-channel power MOSFETs Q_1 and Q_2, realizes the functionality of configuring the power bus. The two tele-command provisions, "charge mode ON/OFF", and "discharge mode ON/OFF", can configure the battery to get charged or discharged independently. Charging is enabled with Q_1, while discharging with Q_2.

The default value of "discharge mode enable" is zero, and the default position of S_2 is ON. Hence, turn ON of the the switch Q_2, happens with, turn ON of the power bus. With rover OFF, the battery discharge mode gets disabled automatically. With rover ON, discharge mode gets enabled, as the 5V, reference voltage is generated after the switch S_1.

Discharge mode gets enabled, whenever Rover ON command is issued from ground checkout (GC) or Lander Craft (LC), for the command duration of 150ms, prior to the closure of S_1. This helps in verifying the battery health, as mentioned in section IV(F). A similar check happens during the automatic wake-up of the Rover, with battery getting connected in discharge mode for $\approx 20ms$, from the thermal logic. The battery health check or the solar generation check happens, as the 18Ω heater is connected to the Normally Closed (NC) contact of the Relay switch S_1. A voltage of 18V, developed across this heater, initiates the rover wake-up by activating the relay switch S_1. Now the 18Ω heater gets disconnected and Power Bus gets activated.

VI. Conclusion

A configurable 50W power bus design for a lunar rover is presented . The design improves the survivability of the rover considering the harsh environmental conditions of lunar surface. The proposed configuration guaranties the operation of the rover, in case of a short mode failure of the battery,

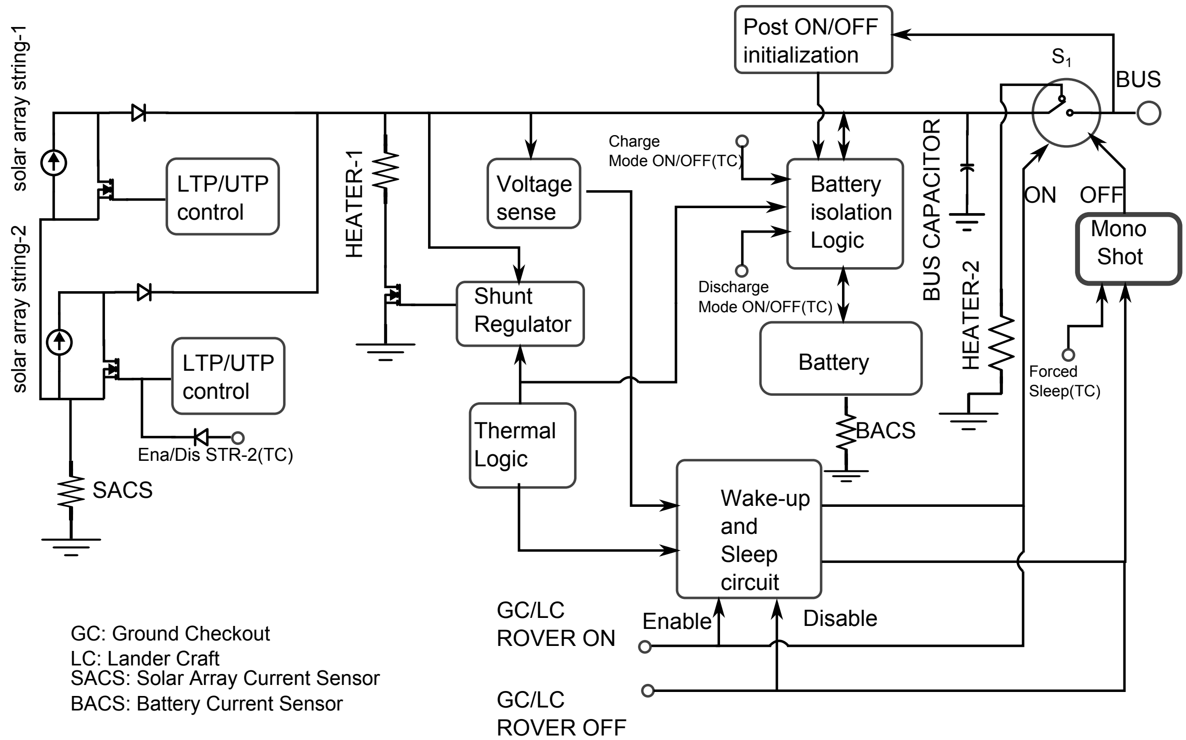


Fig. 4. Proposed Block diagram of the Lunar Rover Power System

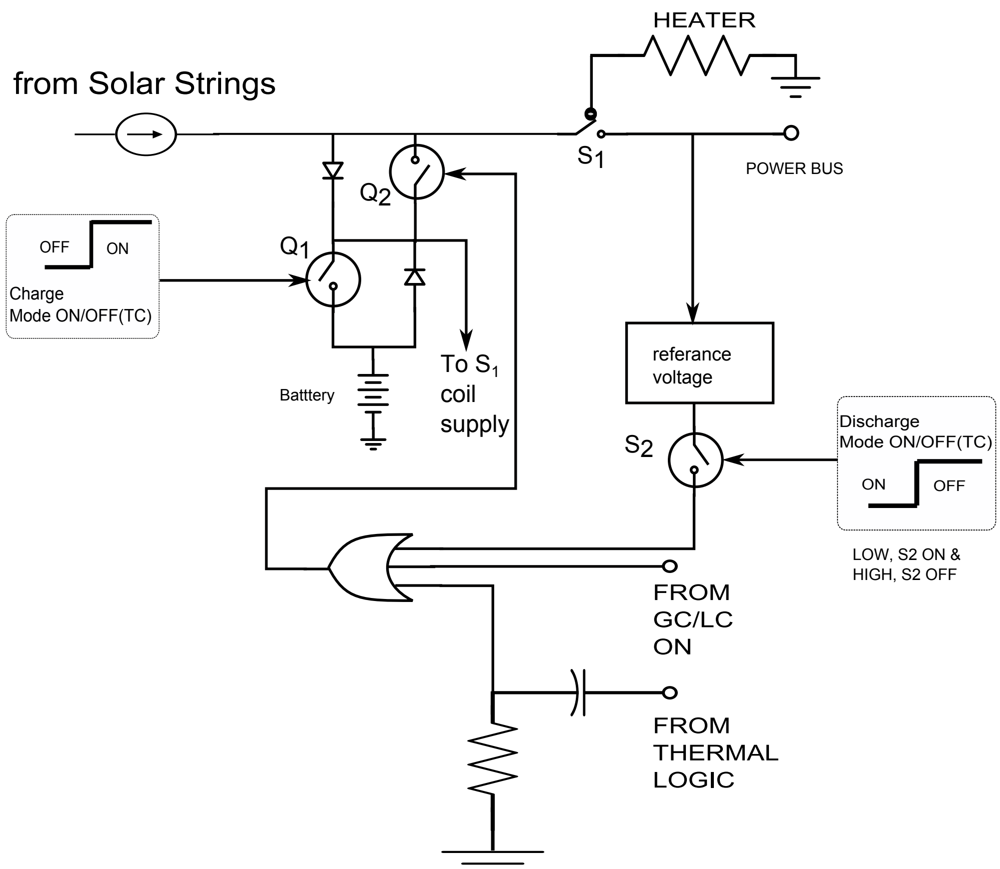


Fig. 5. Schematic diagram of Battery Isolation Logic

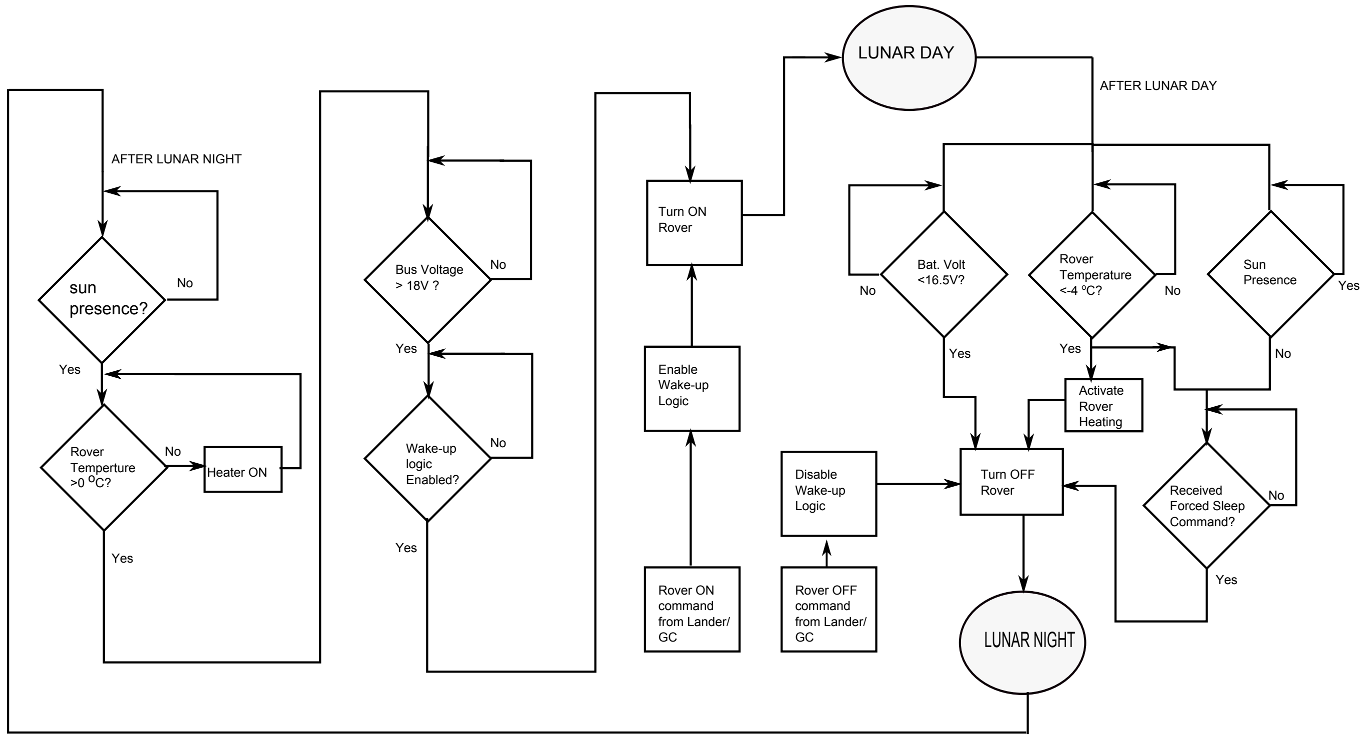


Fig. 6. Logic flow diagram of sleep & wake-up function

while providing the most suitable battery tied power bus for normal operation of the rover. The design complexity is kept minimum and operationally address many of the possible failure scenarios imposed by lunar environment and unknown terrain. The built in reconfigurability feature of the power bus, helps in improving the effective operational life of the rover.

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